Applications and Issues of GIS as Tool for Civil Engineering Modeling

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ABSTRACT: A tool that has proliferated within civil engineering in recent years is geographic information systems (GIS). The goal of a tool is to supplement ability and knowledge that already exists, not to serve as a replacement for that which is lacking. To secure the benefits and avoid misuse of a burgeoning tool, engineers must understand the limitations, alternatives, and context of the tool. The common benefits of using GIS as a supplement to engineering modeling are summarized. Several brief case studies of GIS modeling applications are taken from popular civil engineering literature to demonstrate the wide use and varied implementation of GIS across the discipline. Drawing from the case studies, limitations regarding traditional GIS data models and the implementation of civil engineering models within current GIS are identified and countered by discussing the direction of the next generation of GIS. The paper concludes by highlighting the potential for the misuse of GIS in the context of engineering modeling and suggests that this potential can be reduced through education and awareness. The goal of this paper is to promote awareness of the issues related to GIS-based modeling and to assist in the formulation of questions regarding the application of current GIS. The technology has experienced much publicity of late, with many engineers being perhaps too excited about the usefulness of current GIS. An undoubtedly beneficial side effect of this, however, is that engineers are becoming more aware of GIS and, hopefully, the associated subtleties. Civil engineers must stay informed of GIS issues and progress, but more importantly, civil engineers must inform the GIS community to direct the technology development optimally.

INTRODUCTION

Fundamentally, we as civil engineers—regardless of emphasis—share one characteristic in that we are all problem solvers. Civil engineers solve problems through modeling, design, planning, and evaluation. Instrumental to these processes are the tools that we employ to accomplish our task. A tool that has proliferated within civil engineering in recent years is geographic information systems (GIS). Specifically applied to modeling civil engineering phenomena, GIS has been recognized in a majority of the civil engineering disciplines as a beneficial technology. This fact is illustrated by the growing number of articles finding their way into civil engineering journals and conference proceedings, in addition to the handful of special publications devoted to GIS in civil engineering [e.g., Goodno and Wright (1992); Frost and Chameau (1993); Frost (1997)]. Both researchers and practitioners in civil engineering have embraced GIS. This rapid acceptance has elevated GIS to buzzword status.

Regardless of its seeming acceptance, what is certain is that GIS technology was not developed with the intention of being a tool for civil engineering modeling; otherwise engineers would not put forth such undue effort in fitting various models to GIS. In this context, civil engineering modeling refers to the application of mathematical simulation to civil engineering-related problems for the purposes of understanding a physical process or providing a predictive tool. Interestingly, the earliest antecedent of GIS has been traced to the University of Washington where geographers and transportation engineers developed quantitative methods in transportation studies in the early 1950s (Coppock and Rhind 1991). Even so, the development of GIS resulted from a need for automation by organization that were faced with the overwhelming resource strain of map manipulation for large projects. Thus, the technology has most commonly been used for automated mapping and facilities management in the utilities and government sectors. Commercial GIS software that has gained such wide use reflect these origins and, as such, is primarily concerned with location and attributes.

GIS has been criticized as a technology in search of applications. Perhaps more appropriate is the proverb: ''give a child a hammer and he will find that everything needs hammering because everything looks like a nail.'' Yet, simply because a tool was not developed for a certain application does not preclude its potential usefulness. But to secure the benefits and avoid misuse, engineers must understand the capabilities, limitations, alternatives, and context of the tool. The aim of this paper is to present a broader view of GIS in the context of civil engineering modeling and discuss a variety of issues pertaining to GIS-based modeling that have not typically been covered in significant depth within application-specific publications. Thus, the reader should obtain a broader understanding of the tool they employ (or plan to employ) and gain an appreciation for a related set of issues that will affect the future use of spatial information systems in the discipline of civil engineering.

The present paper begins with the following section, Common Benefits, by outlining several reasons that GIS is used as a supplement to engineering modeling. Case Studies Across Civil Engineering describes several brief examples of GIS modeling applications taken from popular civil engineering literature to demonstrate the wide use and varied implementation across the discipline. Drawing from the case studies, limitations regarding traditional GIS data models and the implementation of civil engineering models within current GIS are identified and countered by discussing new developments of Next Generation GIS. The paper concludes by highlighting the real potential for the misuse of GIS in the context of engineering modeling in Misuse and Liability and suggests in GIS Education that this potential can be reduced through education and awareness.

COMMON BENEFITS

One must assume that there are indeed significant benefits gained from the use of GIS for engineering modeling in light of the spectrum of applications using this tool. Bennett (1997)

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states that GIS offers a virtual environment within which decision makers and scientists can explore theory and evaluate competing management strategies. GIS has yet to fully reach this lofty plateau because current generation GIS provide a mediocre modeling environment at best. However, commercial GIS does provide means to handle certain forms of spatial data, perform limited spatial analysis, and produce cartographic output. The merits of current GIS as a modeling tool are discussed in Next Generation GIS.

Data Handling

GIS software is unique in its ability to capture, store, and manage spatially referenced data such as points, lines, and polygons (vector data model), or as continuous fields (raster data model). Simply used as a spatial database, GIS assists in modeling applications through handling a special form of data that would otherwise be compromised or impossible to store in aspatial databases. This is likely the most compelling reason for using GIS and is the most commonly cited advantage. Before having the ability to handle large volumes of spatial data, engineers were resigned to model on a site-specific basis or otherwise employ gross abstractions. Relational database features of many commercial GIS help to protect data integrity and maintain data consistency. Query languages and user interfaces permit rapid modification of parameter values (i.e., attribute data assigned to spatial entities or fields). Convenient and quick updating of model parameters is a significant advantage for models that rely on in situ determined parameters.

GIS does not only serve as a database for parameter data. Qualitative and quantitative data can be integrated through spatial relationships rather than through relationships between attributes that may not exist (Frost et al. 1997). This is most commonly done using the overlay function of a GIS where multiple maps are either visually or topologically combined. Visualization of data using the graphic features of GIS can assist the engineer in verifying data and information pertaining to the model and its application.

Elevation data are worth singling out, as they are common to many applications of engineering models. Robust GIS are among a small set of software that contain facilities for constructing and importing digital elevation models (DEMs) and triangulated irregular networks (TINs). Information such as slope and aspect can be subsequently derived from DEMs and TINs using software specific functions. Such information is the foundation on which many models, including slope stability and surface runoff models, are based.

Model Application

GIS supplies a framework in which to model spatially resident engineering phenomena. Distributed models can take advantage of the implicit topology of geographic entities in the vector model or can consider the effect of surrounding cells in a raster-based model (Kiremidjian 1997). Site-specific (or data) models, although possibly not explicitly spatially dependent, can be extended to calculate results on a regional scale with relative efficiency.

Engineering analyses that have been traditionally map based, such as flood forecasting, benefit from efficiency in performing spatial operations that have been performed manually in the past. Some large overlay processes or subbasin delineation would potentially take weeks if done in the traditional manner (Wong et al. 1997). Spatial operations of GIS do not only supplement such traditional map-based modeling. Common operations such as area computation, flow path length measurement, and nearest distance determination (through euclidean or network space) can be used to conveniently derive model-dependent parameters.

Results Interpretation

To many, the most obvious and appealing feature of GIS is the ability to present analysis results in map form. The production of cartographic quality maps or presentations can certainly provide support in many pertinent decision processes. Additional advantages can be gained using other graphic features of GIS. Through interactive visualization of model results, the reasonableness of predictions may be assessed. Critical areas can be identified where more rigorous analysis is required. Visualization can be supplemented by spatial and aspatial queries of model results. Such queries help in identifying possible correlations between input parameters and model predictions.

CASE STUDIES ACROSS CIVIL ENGINEERING

Civil engineers are discovering a wide variety of uses for GIS technology. Unfortunately there is not a common forum for civil engineers to disseminate ideas and criticisms about GIS and its application. Much can be achieved from analyzing the diverse applications of this technology that span civil engineering. The aim of the short case studies cited herein is to highlight the goals of each application, the respective implementation processes, the end product(s), and pertinent conclusions drawn by the engineers involved. In doing so, the wide variation of implementation strategies for GIS-based modeling will be illustrated. The case studies will also introduce many of the issues discussed in the following sections. Examples have been taken from refereed civil engineering sources to avoid affiliation with specific software or predisposition to particular GIS implementation strategies. An attempt has been made to illustrate the breadth of GIS use in civil engineering.

Case Study 1: Storm Water Pollution

Nonpoint sources of water pollution are recognized as having greater importance than point sources in many locations. The stochastic nature of nonpoint pollution processes and the large data requirements make such modeling difficult. Wong et al. (1997) embedded an empirical data model into a vector GIS, specifically, ARC/INFO running on a UNIX platform, for analyzing the Santa Monica Bay, Calif., watershed. The model uses data on local rainfall, land use, drainage, and local and national water quality to estimate pollutant loadings. Spatial dependence of the model is limited to the subbasin area. Wong et al. (1997) view the GIS as a back-end database-management tool and an interface to the urban runoff model.

GIS implementation of the model required three coverages (spatial data layers): (1) Land use; (2) subbasins; and (3) catchment. These coverages were scanned from USGS maps. Delineation of subbasins was performed manually prior to scanning. Rainfall and runoff coefficient information were associated with land use as coverage attributes. With all relevant attributes, the three coverages were unioned (overlain) and the empirical model was applied using the calculation functions of ARC/INFO. The analysis was used to determine basins and land uses producing the most polluted runoff. Model output was used to design a monitoring program that has become the framework for the Los Angeles County Department of Public Works monitoring program for the areas draining into the Santa Monica Bay. Wong et al. (1997) point out that by ''(u)sing the GIS/model it is easy to position monitoring stations at locations that will sample a minimum fraction of the runoff. . . . The overall framework [GIS and model] takes advantage of the built-in relational database management technology of the GIS to construct an accurate and detailed database.''

Case Study 2: Sediment Transport

A geomorphic-based hydrologic and sediment transport model was embedded into a raster GIS by Mashriqui and Cruise (1997). The modeling approach was based on the grouped response unit concept. This approach was seen as less data intensive than most grid-based methods and, thus, more efficient and easier to execute over large areas through GIS. The model employed was the chemical, runoff, erosion from agricultural management systems model, which is composed of a set of simple equations. Spatial parameters of the model include drainage area and slope.

Drainage boundaries were delineated manually on a 7.5-min USGS topography map and digitized using ARC/INFO running on UNIX. Polygons representing distinct soil groups were also digitized at the same scale from a soil survey map. Rainfall point data were imported and interpolated into regions by creating Theissen polygons in ARC/INFO to account for spatial distribution. Land-use data were remotely sensed and classified using ERDAS Imagine, also running on UNIX. The database created using ARC/INFO and ERDAS Imagine was transferred to Map II, a MacIntosh-based GIS, for subsequent modeling. This particular software was chosen for its user friendliness and ability to interact with the user. Homogenous computational units were identified manually through heads-up digitizing. Finally, spatial parameters were calculated and data coverages were overlain using Map II functions before applying model equations with Map II. Mashriqui and Cruise (1997) conclude that ''GIS was used as a link between cartographic data and model parameters. . . . Techniques used in this study provided an efficient way of estimating the effects of spatial variation of slope, soil type, and land use of a watershed on the runoff and sediment yield.''

Case Study 3: Solid Waste Collection

Waste collection comprises a significant part of the expense of municipal solid waste management; therefore, collection optimization has the potential to yield large savings. For metropolitan regions, one issue is how to effectively distribute the collection crew and vehicles. Chang et al. (1997) studied the ability of GIS used with a multiobjective programming model for vehicle routing and scheduling to analyze the optimal path between a given origin and destination in a waste collection network. In this context, optimization seeks to minimize total collection distance, costs, and time.

ARC/INFO contains built-in routing and scheduling procedures (i.e., SPATIALORDER and COLLOCATE) for modeling flow through topological networks, which are easily constructed in the GIS. Unfortunately, these procedures are not considered to be efficient enough for use with complex management problems. This is because multiple objectives must be considered and several types of vehicles should be dispatched to the waste collection network. Stronger analysis was afforded by connecting ARC/INFO with the LINDO optimization software package using a FORTRAN interface program, all operating under the Solaris operating system.

The system created determines the network pattern in each subdistrict of the Lin-Ya district, Taiwan. Attributes of current population distribution and collection points were manually assigned to each network segment. The average output of solid waste over all of the links in the district was estimated. Data were then transformed for use in LINDO so that optimal routing and scheduling could be determined. In this was, the demand for the waste disposal of the entire district could be predicted for several social, economic, and environmental parameters. ''(B)uilding such analytical capabilities with GIS for developing effective routing and scheduling strategies could be crucial to create a more efficient solid waste management practice'' (Chang et al. 1997).

Case Study 4: Seismic Slope Stability

A vector-based GIS framework was utilized for applying rigorous Newmark's displacement method (Newmark 1965) for assessing relative hazard due to earthquake-induced landslides (Ho and Miles 1997; Miles 1997; Miles and Ho 1999). Hazard analysis was performed for the East Bay Hills near Berkeley, Calif. Newmark's method is both data and computationally intensive, requiring critical acceleration (based on static factor of safety), acceleration time histories, and the double integration of those parts of the time histories that exceed the critical acceleration.

Input coverages consisted of a slope coverage derived from a USGS DEM, a soils coverage, and a digitized trace of the Hayward fault. Estimated shear strength and unit weight attributes were assigned to polygons of a manually digitized soil survey map. The three input coverages were overlain to create the final parameter coverage. The infinite slope model, embedded into ARC/INFO running on Solaris, was used to compute static safety factors and critical acceleration values for each polygon under dry and saturated conditions. Earthquake ground motions were stochastically simulated for a set range of source-to-site distance intervals. The simulation was coded in Mathsoft MathCAD for Windows to exploit the robust mathematical facilities required for the ground motion model (e.g., fast Fourier transforms) and permit understanding through interaction with the simulation. ASCII files describing 20 simulated earthquakes having a magnitude of 7.0 were generated. An interactive arc macro language (AML) was written for coverage, time history, and analysis management. Among the functions of the AML is the selection of appropriate time history files based on nearest distance calculations between the fault and each polygon centroid.

By way of an interapplication communication (IAC) call in AML, arguments are passed to an in-house C program to compute displacement as the AML iterates over each polygon in the coverage. Hazard maps expressing displacement in centimeters were plotted from analysis results. The value of such intensive methods was justified in Miles (1997): ''by using the rigorous analysis for regional hazard assessment, efforts can be focused on obtaining quality data rather than identifying and quantifying possible errors with analysis simplifications.''

Case Study 5: Liquefaction

Despite the proliferation of GIS, functionality required by most engineering design cases is lacking in commercial systems and must be supplemented with other engineering and visualization tools. Luna and Frost (1998) tied together ARC/INFO, Geo-statistical Environmental Assessment Software (Geo-EAS), Groundwater Modeling System (GMS, 3D subsurface visualization software), and in-house developed C programs to create an interactive spatial environment for evaluating soil liquefaction potential (LPI) at a site-specific scale. A primary objective of the environment is the provision of user interaction in which to permit both numerical and visual analysis.

ARC/INFO fulfills the role of the database and user interface. Geo-EAS serves to replace the inflexible interpolation capabilities of ARC/INFO. GMS permits the characterization of a subsurface based on borehole data and allows the interactive visualization of 3D information. The independent C programs were previously developed to perform the liquefaction analysis. These programs had to be modified to work in conjunction with the GIS database. Several Solaris shell scripts and AML routines that perform data transfer and make system

calls between applications bind the interconnected system. LPI evaluation requires information gathered from either a cone penetration test or a standard penetration test, in addition to modeled earthquake parameters. LPI has no explicit spatial dependence, but point data selection can be performed using spatial operations of ARC/INFO (e.g., querying, buffering, overlay). Spatially distributed results of the liquefaction analysis are interpolated and processed to yield isolines describing LPI. Luna and Frost (1998) concluded that ''(t)he system allowed successful interaction with the user to the point of performing a parametric study of liquefaction by varying the earthquake magnitudes and peak ground accelerations of the input motion.''

Case Study 6: Distributed Rainfall Runoff

A software environment, real-time interactive basin simulation (RIBS), was developed by Garrote and Ignazio (1997) for real-time flood forecasting using distributed models. Work on distributed hydrology has, in many respects, been driven by the availability of information such as DEMs and radar rainfall maps. Thus, spatial data play an integral role in the development of distributed hydrological modeling tools. But the inability of commercial GIS to effectively assist modelers in actual coding for distributed model implementation and maintenance lead to the construction of an alternative means.

RIBS is an independent software package (i.e., not based on commercial GIS) of C++ base classes that can be employed and extended by modelers to implement a wide range of distributed rainfall-runoff models. The objective of RIBS is to provide a unifying framework to manage the variety of processes required for a real-time flood forecasting system. The framework allows for integration of any model that shares the same data representation as RIBS. Spatial data are handled in a raster format. Database facilities in RIBS are not as rich as those supported in a database management system (DBMS) because the database is simply a collection of computer files. These files are sufficiently structured and classified to provide relatively efficient management. Variables residing in the database are grouped to higher levels to assign hydrological semantics and attach functionality. Object viewers allow the retrieval of variables and afford interactive modeling capabilities. This permits, for example, the analyses of different aspects of a basin state as a storm progresses, the evaluation of the runoff-generation potential of different basins, the creation of hydrographs at selected locations, and the generation of reports on model variables. RIBS is unique in that, ''(t)he user can navigate through key model components getting information about their current or past state or can request that additional computations be performed. In addition to providing graphic access to model results, this interactive approach to model management allows the user to understand how model results were generated. The model can thus be used more effectively as a basis for decision making'' (Garrote and Ignazio 1997).

Discussion of Case Studies

Presentation of the six case studies offers an interesting view of GIS in the context of engineering modeling applications. The disciplines of civil engineering are well represented. Those that are not represented have likely exploited GIS for nonmodeling applications, for example, bridge life-cycle management (Itoh et al. 1997).

The case studies illustrate several notable trends. For the most part, no single software package was solely sufficient, nor was GIS used explicitly for model application. Often, in-house solutions were required. No consensus approach to connection of the engineering models and GIS is apparent, with

at least one case study exploiting multiple strategies. In Case Studies 2 and 4, connections spanned more than one operating system. Models in five of the examples are data or lumped models that are simply dependent on parameters derived through spatial operations. Case Study 6 is the only case where a distributed dynamic model was implemented, and this was afforded by the development of a solution independent of commercial GIS. Among the examples, the development of interactive systems for model investigation and decision support is more common than problem-specific analysis.

Most notable among the trends is the popularity of ARC/INFO from the Environmental Systems Research Institute (ESRI), Redlands, Calif., which is used in every instance except Case Study 6. Obviously, this is not because it possesses robust modeling capabilities as only one case study uses the package for complete model implementation. The prevalence of ARC/INFO can be attributed to at least four reasons: (1) Software includes flexible spatial data input facilities, primarily related to digitizing; (2) ESRI has made the software available for a wide variety of operating systems and platforms; (3) many organizations such as the EPA, NOAA, and USGS, who are primary data providers in the United States, release data in the ARC/INFO format; and (4) with respect to GIS in universities, ARC/INFO is often the legacy system in departments of long-standing GIS use in the United States; these include geography, landscape architecture, regional planning, forestry, and wildlife management. In light of these reasons, ARC/INFO may be commonly adopted by researchers largely because of the availability of the software and the knowledge pertaining to it, rather than as an appropriate tool for engineering modeling.

NEXT GENERATION GIS

Future developments of engineering GIS seek to extend the spatial data modeling and analysis far beyond that of the current generation GIS. The next generation of GIS should blur the distinction between model routines and GIS functions through the fusion of models and spatial representation (Raper and Livingstone 1995), as demonstrated in Case Study 6. This can be achieved by addressing the functionality, data models, and interfaces of conventional GIS.

Engineering Models

The six case studies demonstrate that the current generation of GIS possesses limitations with respect to model construction and implementation. Even in the single instance where desired functionality was available (Case Study 3), the functions were seen as being too inefficient and inflexible to be useful. In the case of hydrological functions, which are relatively common in commercial GIS, models are rarely state of the art and often have undergone modification that may or may not be documented by the GIS vendor. Conventional GIS development has been data led, and because of this, GIS is good at handling spatial data as exact entities or discretized fields. Therefore, GIS has not grown out of consideration of modeled phenomena or numerical methods employed (Livingstone and Raper 1994).

Engineering models are concerned with state, process, and relationships, whereas position-based GISs simply consider location. Burrough and Frank (1995) note that there is a large gap between the way that spatial and temporal phenomena can be perceived and modeled and the conceptual foundation of current commercial GIS. Thus, GIS removes two essential ways in which engineers approach problem solving, that is, perception—how we view a problem, and representation—how we abstract a problem. The consequence of making perceptual and representational compromises can be a lack of confidence on the part of the engineer regarding model fitness.

Data Models

As illustrated through the case studies, the way in which models are formulated and problems are solved is largely driven by the particular GIS used. The data models that comprise the foundation of current GISs were created for the purposes of easy processing rather than simulation (Burrough 1997). Because of this, a spectrum of dissimilar phenomena is being modeled using the same or similar data model. It is unlikely that there is a universal data model that is appropriate in all instances (Livingstone and Raper 1994). Present-day GIS employ a static geometry that cannot represent and store complexities and dynamics. Therefore, GIS is poor at capturing spatial changes, representing uncertainty in boundaries, and representing interacting objects. In most instances GIS abstracts the real world to a 2D surface.

A large number of models relevant to civil engineering have a strong temporal association. However, GIS data models were not designed to explicitly represent time. Engineers are currently forced to handle temporal change through the implementation of time slices—entire layers associated with particular instances in time—or photographs that do not permit relative change among individual events and processes (i.e., objects). A collective approach to time management does not represent information such as mutations, transitions, and motion (Yuan 1996). Mutation refers to change occurring to the internal attributes of objects. Transitional changes compare the state of an event or process at different locations. Motion or movement describes an object, which travels from one location to another. Research concerning temporal GIS, including work previously cited, has focused on transitional change, and further progress regarding mutation and movement is required.

The need for a 3D framework for modeling subsurface (e.g., Case Studies 4 and 5) and atmospheric (e.g., air pollution) phenomena is clear. This area of research garnered considerable attention from the GIS community in the late 1980s (Raper 1989), but 3D modeling has not found its way into mainstream GIS. This is likely the result of vendors' perception of small market demand and difficulty on the part of developers in extending traditional GIS metaphors; for example, overlay and buffering, to a third dimension. Other 3D software environments are primarily oriented toward visualization or are developed for a specific application (e.g., petroleum geology). Of late, research efforts in GIS have experienced a rebirth of sorts in the context of virtual reality and GIS (Williams et al. 1998). Motivation of this research appears to be technology driven, focusing on providing a new interface to conventional GIS. Nonetheless, study in this area is encouraging.

Object Orientation

Object-oriented methods, which can afford higher-level semantics, are the catalyst behind the next generation of GIS for modeling. The advantage of object orientation being that underlying data structures, or means by which data are stored, do not influence representation. Different object-oriented GIS employ different mechanisms for interfacing spatial and aspatial data. Some systems employ object-oriented databases with unified storage (e.g., Laser-Scan Gothic, Cambridge, England); whereas others use an object-oriented language to provide higher-level meaning to data stored in a relational database (e.g., Smallworld GIS, Cambridge, England).

Raper and Livingstone (1995) conceptualized a class structure, OOgeomorph, which is readily applicable to handling point data in four dimensions. OOgeomorph models geomorphological phenomena through classes of form, process, and material. Geographical location and time are treated as properties of the initiated objects. This approach to spatial representation avoids planar enforcement, and thus, can represent complex, rapidly changing phenomena as well as overlapping objects. Geographic Modeling System (GMS), a prototype, was designed to abstract from reality natural systems for the purposes of simulation modeling (Bennett 1997). GMS selects conceptual data models most suitable to the features of the modeled system. These data models are encapsulated within semantic objects such as data structures, mathematical equations, and topological relations, which are then translated into computer code for implementation. A conceptual layer is provided by User Analysis and Project Environment, which utilizes an object-oriented data model that is mapped to any underlying database through GIS-specific drivers (de Oliveira et al. 1997). In this way, the underlying data structure does not drive representation, and both the field (raster) and entity (vector) views can be combined. The interface permits data and process models to be used together and supports temporal modeling via a subclass, which can represent continuous or discrete time. Explicit relationships between objects can be defined using object-oriented principles of inheritance and aggregation. Work at the Argonne National Laboratories has led to an object-based modeling software called OOGIS (Korp et al. 1996). OOGIS provides spatially optimized object representation and direct linkage to underlying data and object behaviors using "self-describing" objects. Objects can be defined as context sensitive, for example, visual representation can vary in accordance to distance. OOGIS employs a single object-oriented language (Smalltalk) for query, scripting, and programming.

OPEN SYSTEMS

Next generation GIS strive to alleviate many of the limitations of current GIS when applied to modeling through addressing current data models, functionality, and interfaces. These developments are promising but, as problem solvers, engineers are faced with working with the tools that are immediately available. This is, in large part, the reason why so many engineers integrate multiple applications with GIS to facilitate their particular task or software need. Much has been written on the subject of the integration of models with GIS. Borne out of this discussion are countless terms describing the strength of connection. Weak connections, usually typified by static file transfer and disparate user interfaces, may be referred to as loose coupled, shallow coupled, linked, or external. Stronger connections, which are associated with GIS-specific utilities and a coherent user interface, may be referred to as tight coupled, deep coupled, embedded, or internal. Rao et al. (1997) defined two or more components that are glued together in any manner through means of interapplication communication or distributed computing platforms, such as DDE, OLE/COM, CORBA, or ACL, as an interconnected component application (ICA). The enumerated terms used by the GIS community for the construction of an ICA suggests that there are recipes or guidelines in which to follow. ICA development is much more of an art in that there is no optimal approach or generic set of procedures. Developers must consider the functionality that is desired and the functionality that is offered by available components. They must consider the type of interconnection and identify what cannot be accomplished by existing components. Developers must often perform modifications to existing components to facilitate interconnection.

Open Systems Paradigm

What then is the solution to current GIS that do not have the requisite functionality, flexibility, or robustness? Engineers
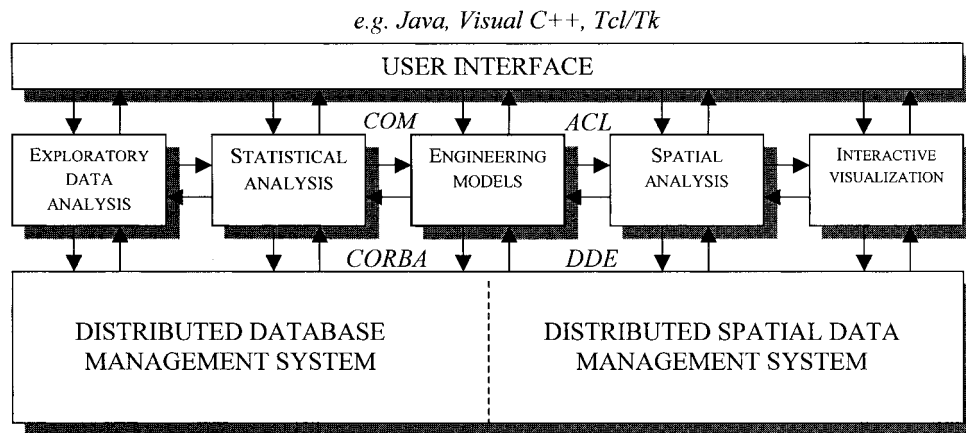
FIG. 1. Illustration of Open Systems Approach to Spatial Modeling

can demand that GIS vendors increase the functionality of their products. In many respects vendors have responded to demands, with the result more often than not being functions that are neither flexible nor robust. Considering this strategy, where do vendors draw the line? Vendors are producers of GIS and cannot possibly pander to all disciplines. Certainly GIS software should not become all-encompassing, monolithic solutions (Lilburne et al. 1997). Vendors have an option of creating product specific drivers in which to interface third party solutions. Unfortunately, this alternative is wrought with difficulty because vendors will not be able to provide drivers for all software or may simply view driver production as the responsibility of the third party developers. The ideal alternative lies in the open systems paradigm (Albrecht 1999). Open systems require the portability and integration of many components such as hardware platforms, operating systems, database managers, and user interfaces (Magalhaes 1994) through standards or, more preferably, operational models. The issue of the development of standards and operational models is treated in more detail at the end of this section.

The open systems paradigm avoids a GIS-centric or GIS-specific solution where GIS or a particular GIS product is treated as the integrator. The desire for this alternative is illustrated in Watkins et al. (1996), which reports the results of a survey conducted at the Second International Symposium/Workshop on GIS and Environmental Modeling, which asked participants to indicate the relative importance of specified capabilities for environmental GIS. Survey results indicate that those surveyed see standard facilities for interconnecting applications and the ability to embed GIS functionality into existing models or applications as more crucial than added functionality or even next generation data models. Standard or easy to use interconnection protocols and components will allow developers to painlessly create ICAs that integrate engineering applications for exploratory data analysis, model implementation, statistical analysis, and visualization. Under the open systems paradigm, an ICA will seamlessly sit atop one or many aspatial and spatial databases (e.g., ESRI, Spatial Data Engine (SDE), Spatial Data Cartridge (SDC) while interaction is provided by a common user interface. Applications and databases should be able to reside on different platforms that span multiple operating systems. Developers must be able to construct an ICA under any popular environment such as Java, Visual C++, or Tcl/Tk. An example of an open system ICA is illustrated in Fig. 1.

GIS vendors are beginning to respond to the demand for GIS components or toolkits by marketing GIS function libraries or by exposing software operations for use in other environments. Current alternatives include ESRI MapObjects; Laster-Scan Gothic Integrator; Universal Systems Ltd.

CARIS++ (Fredericton, New Brunswick, Canada); Intergraph GeoMedia (Huntsville, Ala.); Graticule MapTools (Leeds, England); Object/FX SpatialX (St. Paul, Minn.); and Plexstar ClearSpace (Fairfax, Va.). So far the alternatives are relatively lightweight in that they are not intended for engineering modelers and simply allow developers to embed maps and a limited degree of map interaction (e.g., pan and zoom). These solutions have no facilities for constructing, importing, or analyzing elevation information such as DEMS or TINs. Such facilities are indispensable across the spectrum of engineering applications. The GIS community may not yet perceive the need for robust components or may prefer to maintain a GIS-centric view. To date, little or no research has been published in the area of engineering modeling using such components or toolkits.

Open GIS

The GIS community has recognized the need for open GIS (not to be mistaken for the open systems paradigm) through the evolution of the open geodata interoperability specification (OGIS) by the open GIS consortium (OGC). OGC is a broad-reaching alliance of research centers, software vendors, and system integrators. Their vision is the full integration of geospatial data and geoprocessing resources into mainstream computing, and the widespread use of interoperable, commercial geoprocessing software throughout the global information infrastructure (Buehler and McKee 1998). OGC defines open GIS as seemless access to heterogeneous spatial data and geoprocessing resources in a networked environment. OGIS attempts to provide a comprehensive suite of interface specifications that enable developers to write interoperating components. The primary goal of the OGIS formal, abstract, and implementation specifications is the utility of access to spatial data across remote locations, regardless of format or product of origin. However, OGIS is not a data standard, but rather an operational model designed to dynamically translate spatial data, which can be accessed by applications through basic operations. The implementation specification seeks to achieve geoprocessing interoperability by establishing a standard way for OGIS compliant products to use distributed computing platform services (Albrecht 1999). Thus, an OGIS-compliant product that employs, for instance, COM technology, will be able to communicate or interact with another OGIS-compliant product that is based on CORBA technology. The advantages of this being that, hopefully, by being OGIS compliant a product will be compatible with the open system paradigm.

At the time this paper was being written, there were still no OGIS-compliant products, although the OGIS specifications

have been baselined and published. This may be the result of vendors attempting to be parsimonious in the way in which they make products "open," as a truly open GIS may not be in a vendor's best interest.

MISUSE AND LIABILITY

A tool, whether it be hardware, software, or a design approach, is refined to its particular use through formalized trial and error. Uncovering design flaws through failure analysis and learning from identified mistakes or misuse has played an integral role in the maturation of civil engineering practice. GIS software (and GIS-based analysis) is being increasingly used in its present state, and most certainly, this trend will continue to grow along with the next generation of GIS. Therefore, GIS use must undergo refinement through understanding gained from misuse and mistakes that ultimately result in failure. Unfortunately, the failure of a GIS-based method or decision support system may not be as visible as the gyrations of the Tacoma Narrows Bridge. (Failure in this context does not refer to the relative success of GIS implementation within existing information technology of private or public organizations.) The most likely failure scenario is that of poor decisions or plans based on GIS output, which leads to monetary loss. However, the proliferation of GIS use in natural disaster hazard mitigation poses the potential for decisions to indirectly lead to death or injury.

Potential for Misunderstanding and Misuse

Engineers who utilize GIS may not appreciate that the effect of GIS-specific data structures and assumptions, such as those relating to capture, storage, analysis, and interpretation of data, may unknowingly lead to distortions and misunderstanding (Burrough and Frank 1995). Several aspects of the case studies serve as potential examples of this statement. In Case Study 4, polygons having finite boundaries are used to represent the distribution of soil properties. In reality, soil properties continuously vary and do not possess explicit boundaries where properties abruptly change. The soil polygons were overlain with the triangles of the slope layer. This created a coverage of polygons, to which the slope stability model was applied, that have no real world meaning. Case Study 2 also used polygons to represent soils groups, but after the polygons were digitized, the soil layer was converted from a vector coverage to a raster coverage (i.e., rasterized), thus distorting the original boundaries to some degree. Case Studies 2 and 5 employed spatial interpolation in their respective analyses. However, in Case Study 2, interpolation was performed on data prior to analysis; whereas, in Case Study 5, interpolation was performed on results subsequent to the analysis. Unfortunately, little research has been done to investigate the effects and differences of the two approaches. Finally, elevation data were required in Case Studies 1, 2, 4, and 6. An important property of elevation data with respect to modeling is the resolution. It is commonly accepted that the degree of resolution plays a role in the outcome of analyses such as rainfall runoff modeling and slope stability. Yet, in none of the case studies were the affects of different levels of resolution investigated. Sensitivity analysis could have been done with only one DEM by resampling the original grid.

Different GIS exploit subtly, or not so subtly, different techniques in performing similar operations. Vendor-supplied documentation regarding such techniques is often lacking. Likewise, engineers usually must adopt novel approaches in implementing the same model with different GIS. This GIS specificity is undesirable because engineers can produce contrasting results when using similar models across particular GIS. A further problem associated with GIS specificity is the reduction of what Downs (1997) calls metacognitive awareness, the self-awareness of the operation and effectiveness of an engineer's knowledge, skills, and abilities. Blind use of default settings of a particular GIS is an example of an instance of low metacognitive awareness. Case Study 6 attempted to enhance metacognitive awareness through interaction with the model's components to understand how results are generated.

Notwithstanding, the term "GIS use" imparts the onus of responsibility to the user. Engineers must not view GIS as an excuse to substantiate uncertain data or analysis through misplaced concreteness or unawareness. GIS use involves manipulating different forms of data through a series of operations. In a decision support context, this process may take on a decidedly empirical and iterative approach to supply a wide range of scenarios. The engineer must be cognizant of the affects of aggregating data, interpolating data, and combining data that are incompatible with respect to resolution or time. Documentation of the operation sequence should be maintained to assist in identifying potential data errors or blunders on the part of the engineer, which will undoubtedly propagate throughout the analysis process. GIS vendors could facilitate this by including the capability to record data lineage, or those operations that have been applied to a particular spatial data set. Error propagation through spatial modeling is admirably treated in Heuvelink (1998) and Burrough and McDonnell (1998). Of course, GIS itself is not the sole source of misuse. Equally likely sources stem from the perception of GIS capabilities and the uses that engineers apply the burgeoning technology to (Openshaw 1997). Engineers must attempt to understand the influence of modifying models that presumably were not developed with the intention of being applied using GIS.

Few anecdotes have been published about the actual misuse of GIS because of the short history of the technology and the hypothetical nature of many applications (e.g., seismic hazard analysis based on scenario earthquakes). One such reference can be found in Monmonier (1995), who uses a case study of the muddled siting of a waste disposal facility in New York to detail the pitfalls of misuse both in attitudes of the decision makers and the actions taken during analysis. Monmonier blamed the siting commission for unrealistic deadlines, excessive reliance on contractor expertise, and the vagueness of the tender for the contract regarding data resolution and quality. Furthermore, the tender merely specified that GIS must be used and did not specify the expected role or use of the technology. Among the problems associated with the contractor were the use of temporally incompatible data layers (a potential blunder for GIS-based risk analysis). Sites within those maps that were newer were more likely to be excluded because of the appearance of greater development. Further inappropriateness was attributed to the use of area centroids in computing the distance between a site and an incompatible structure such as a school, church, hospital, or residence. By not measuring the difference between perimeters, an advantage was given to large sites, where incompatible structures lying just outside the perimeter would not be excluded. Case studies on the failure of general information systems can be found in Sauer (1993).

Liability and Negligence

With the possibility of misuse, engineers must consider issues of liability. The liability status of GIS, unfortunately, is uncertain at best. The information outputs of GIS create many questions that have not been answered in case law or legal literature (Johnson and Dansby 1997). The use of GIS in engineering further confuses the problem because of the large variety of potential applications for GIS. Each application may very well have its own nuance that may not be an issue in

another. Different applications involve different spatial features, attributes, modeling approaches, accuracy requirements, deliverables, and intended audiences. Liability then becomes an issue of negligence.

Negligence arises when an engineer fails to exercise the standard of reasonable care normally expected of an engineer in that situation, and some damage to another results from this failure (Epstein 1993). Currently, however, a standard of reasonable care is not easily established (Epstein 1993). Negligence will likely stem from the use of unfit data, the use of incorrect or incomplete information, the misuse of spatial inputs, and an inappropriate extension of model algorithms. It is likely that inaccurate data and software or engineer error will lead to incorrect outputs. Yet, errors in data, software, and products are unavoidable, and to a limited degree, are acceptable. More importantly, reasonable inputs, etc., can be misrepresented, misinterpreted, or misused by both the engineer and the intended audience.

Thus, engineers must be aware of the sources of misuse on their part and avoid the temptation to abuse the appealing nature of GIS visualization capabilities. An in-depth discussion about the labyrinth of issues surrounding liability is beyond the scope of this paper. Although GIS analysis may seem to some engineers as relatively inert because few cases of misuse have been documented, the discipline of civil engineering will need to extend ethical practices to encompass GIS-based decisions, products, and services.

GIS EDUCATION

For engineers to conduct themselves in an ethical manner, a self-understanding of the potential snares, the reliability, and the relative fitness for use of any GIS analysis or output must be maintained. For many, the first exposure to GIS comes as the result of a specific project or job that necessitated the use of a specific GIS product. In this way, the particular software in which engineers are trained colors the overall perception of GIS and engineers may not benefit from actual education regarding GIS concepts. For example, much GIS education is self-taught or assisted with books having potentially misleading titles such as: ''Understanding GIS: The ARC/INFO Method.''

As has hopefully been demonstrated, education in GIS is not equivalent to training in one or several commercial GIS because how-to manuals do not cover the most critical issues. Unwin (1990) writes that GIS education, as distinct from training, should focus on the nature of spatial information and algorithms, and the relationship of this theoretical foundation to specific applications. Engineers should gain an understanding of spatial properties, spatial operations, scale continuum, coordinate systems, and spatial patterns. More importantly, engineers need to increase their metacognitive awareness pertaining to the affects of abstracting the real world (and the engineering world) through GIS data models and GIS-specific spatial operations.

Recognizing the need for GIS education, what is the best approach to tackling this deficiency? Institutions across the United States and the United Kingdom are offering many forms of postgraduate degrees in GIS. These programs most often reside within an institution's geography department or departments with similar underpinnings, but geography departments, in general, do not recognize the need for multidisciplinary studies for the application of GIS and do not exploit the knowledge or resources of other disciplines that employ GIS (Hamilton and Pappathanasi-Fenton 1994; Marble 1997). Such programs may focus on the production of GIS experts, but it is equally important, or more so, to educate future engineers about GIS in their own fields of expertise (Huxhold and Andrews 1994). Further, the discipline-independent education of GIS will not cater to the nuances of the various fields of application. Thus, to fill the education gap and make good use of resources, universities and organizations should take a comprehensive, multidisciplinary approach to the development of education programs.

Considering the spatial nature of the entire spectrum of civil engineering, it is surprising that college curricula rarely require courses that nurture spatial thinking. Surveying education has in many respects achieved this role. However, many United States curriculums have reduced surveying education from the summer camps of past decades to shallow treatment within engineering measurement courses. With the increasing use of remote sensing techniques, global position systems, and GIS, many civil engineering curriculums should be reassessed to educate spatial thinking and see which courses can be assisted through these new technologies (Sprinsky 1997). The National Center for Geographic Information Analysis has attempted to assist organizers and professors in conducting GIS education or enhancing existing courses with the National Center for Geographic Information Analysis Core Curriculum in GIScience (Kemp 1997).

CONCLUSIONS

GIS is a tool that is quickly becoming a valuable asset to many civil engineers. Discussion of the six examples of GIS across civil engineering was aimed toward disseminating the potential of GIS, the divergent approaches to implementation, and the existing limitations. Many of these limitations may be reduced by the next generation of GIS, which should provide 4D data models through object orientation or yet undeveloped means. Even so, engineers should adopt an open systems approach to spatial modeling to include robust and flexible functionality and avoid GIS specificity. With the growing capabilities and ease of use of GIS, engineers must be wary of the potential for misuse with respect to spatial data, operations, and outputs. To avoid problems of liability, ethical practice must be extended to encompass GIS and the diverse array of applications in civil engineering. Education, rather than training, is the only means in which to serve this end (and memorize the miasma of acronyms).

The point of this paper, assuredly, is not to put every aspect of GIS into question, but rather to simply promote awareness of the issues underlying GIS and assist in the formulation of questions regarding the application of current GIS. Engineers who support the application of GIS cannot be unwilling to conclude that GIS (or specific GIS software) is not able to handle some situations and should not force the technology to do so. It is important that engineers retain the process of perception and representation by not allowing GIS to excessively drive the way in which engineers apply models. There are always alternatives to the prepackaged or ready-to-assemble solutions [e.g., Miles et al. (1999)]. A large majority of models being used with GIS were not developed with consideration to GIS. Engineers should consider the development and investigation of new or modified techniques that are specific to the GIS context. GIS should not fall into disrepute because it is adopted for the wrong reasons or applied with inappropriate assumptions.

GIS has experienced much publicity of late, with many engineers being perhaps too excited about this new technology (Openshaw 1997). An undoubtedly beneficial side effect of this, however, is that engineers are becoming more aware of GIS and, hopefully, the associated subtleties. Civil engineers must stay informed of GIS issues and progress, but more importantly, we must inform the GIS community to direct the technology development optimally. In conclusion, the advancement of GIS technology may very well improve representation and facilitate a wider variety of applications. But as

this front advances issues of spatial data sparseness and data quality, as well as inadequate collection methods, remain.

APPENDIX.   REFERENCES

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